POTENTIOMETRIC-SURFACE MAP, 1993, YUCCA MOUNTAIN AND VICINITY, NEVADA

by Patrick Tucci and D.J. Burkhardt

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Multiply	By	To obtain
kilometer (km)	0.6214	mile
meter (m)	3.2808	foot
square kilometer (km^2)	0.3861	square mile (mi^2)

Temperature in degree Celsius (°C) can be converted to degree Fahrenheit (°F) as follows:

$$°F = 9/5(°C) + 32.$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Potentiometric-Surface Map, 1993, Yucca Mountain and Vicinity, Nevada

By Patrick Tucci *and* D.J. Burkhardt

Abstract

The revised potentiometric-surface map presented in this report, using mainly 1993 average water levels, updates earlier maps of the Yucca Mountain area. Water levels are contoured with a 20-meter contour interval, with additional 0.5-meter contours in the small-gradient area southeast of Yucca Mountain. Water levels range from about 728 meters above sea level southeast of Yucca Mountain to about 1,034 meters above sea level north of Yucca Mountain. Potentiometric levels in the deeper parts of the volcanic-rock aquifer range from about 730 to 785 meters above sea level.

The potentiometric surface can be divided into three regions: (1) A small-gradient area east and southeast of Yucca Mountain, which may be explained by flow through high-transmissivity rocks or low ground-water flux through the area; (2) a moderate-gradient area, on the west side of Yucca Mountain, where the water-level altitude ranges from about 740 to 780 meters, and ground-water flow appears to be impeded by the Solitario Canyon Fault and a splay of that fault; and (3) a large-gradient area, to the north-northeast of Yucca Mountain, where water-level altitude ranges from 738 to 1,034 meters, possibly as a result of a semi-perched ground-water system.

Water levels from wells at Yucca Mountain were examined for yearly trends (1986–93) using linear least-squares regression. Of the 22 wells examined, three had statistically significant positive trends. The trend in well UE-25 WT #3 may be influenced by monitoring equipment problems during the first three years of analysis. Trends in wells USW WT-7 and USW WT-10 are similar. Both of these wells are located near a fault west of Yucca Mountain; however, another well near that fault exhibited no significant trend.

INTRODUCTION

The Yucca Mountain area is being evaluated by the U.S. Department of Energy for suitability as a potential high-level radioactive-waste repository. A 150-km area located about 140 km northwest of Las Vegas in southern Nevada (fig. 1) is being studied extensively. This work is being carried out cooperatively with the U.S. Department of Energy under Interagency Agreement DE-AI08-92NV10874. As part of that study, water levels have been measured to assist in determining the direction of ground-water flow and to provide a basis for future studies that will examine the rate of ground-water flow. In the Yucca Mountain area, the potentiometric surface of the uppermost saturated zone is in Tertiary age volcanic rocks (Waddell and others, 1984). Regionally, saturated Paleozoic carbonate rocks, of unknown areal extent, underlie the volcanic rocks (Robinson, 1985). Yucca Mountain is in the northern part of the Alkali Flat-Furnace Creek Ranch ground-water subbasin in the regional Death Valley ground-water basin (Waddell and others, 1984).

A preliminary potentiometric surface map was made by Robison (1984, p. 4). Since that map was constructed, more accurate water-level corrections have been made to the data resulting in refinement of the potentiometric surface southeast of Yucca Mountain, where the hydraulic gradient is small. The map in this report updates Robison (1984), particularly in the small-gradient area, and the 1988 potentiometric-surface map of Ervin and others (1994). This report also includes data to the east and west of the map by Ervin and others (1994, pl. 1), and presents time-trend analyses for the available water-level data.

PURPOSE AND SCOPE

This report presents a revised potentiometric-surface map based mainly on the 1993 average water levels at Yucca Mountain and the nearby vicinity extending from Crater Flat to Jackass Flats (fig. 2). Discussion includes an explanation of the revised potentiometric-surface map, differences from previously published maps, and an examination of trends in the water levels. Report scope focuses on the

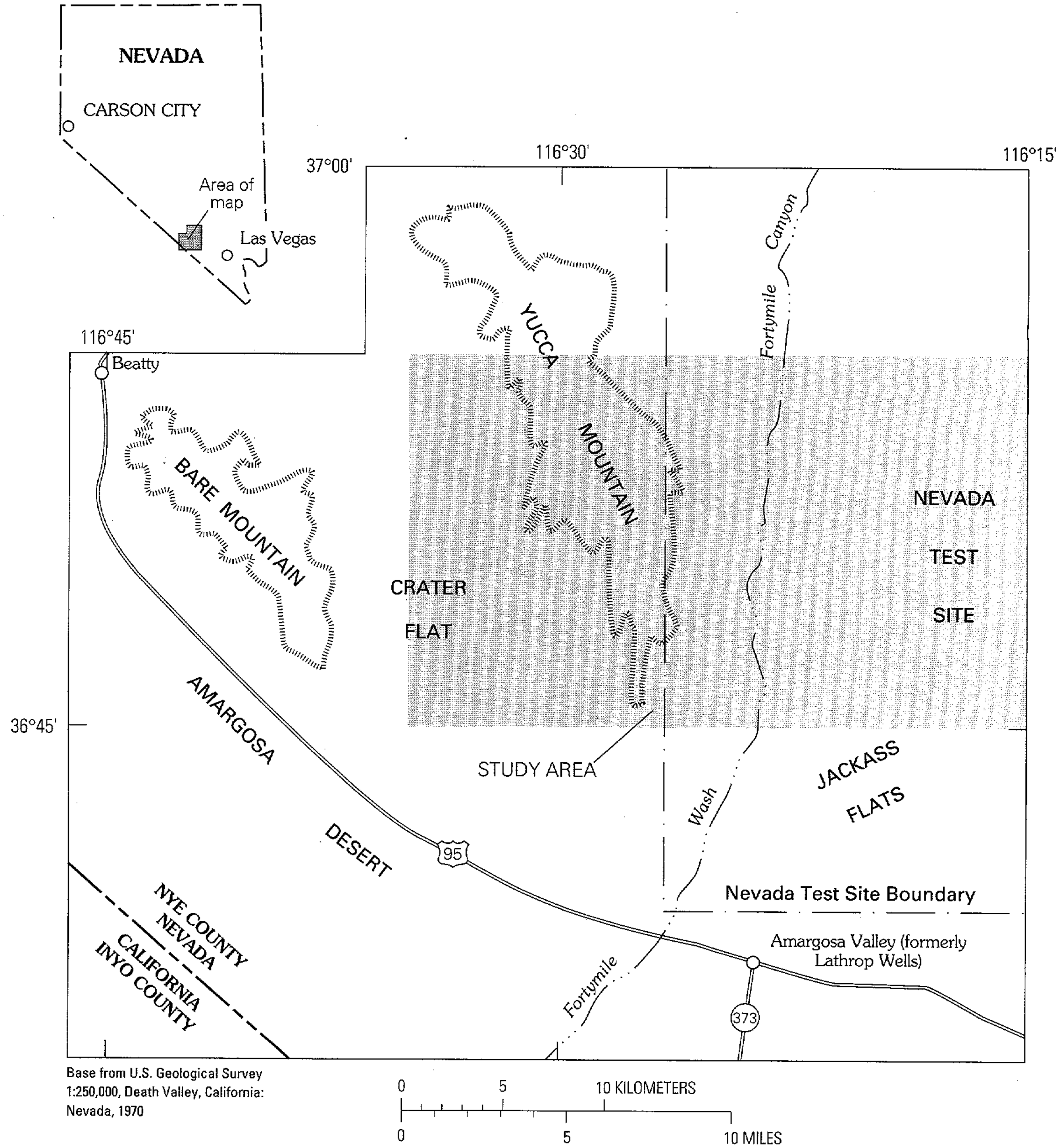

Figure 1. Location of Yucca Mountain and vicinity.

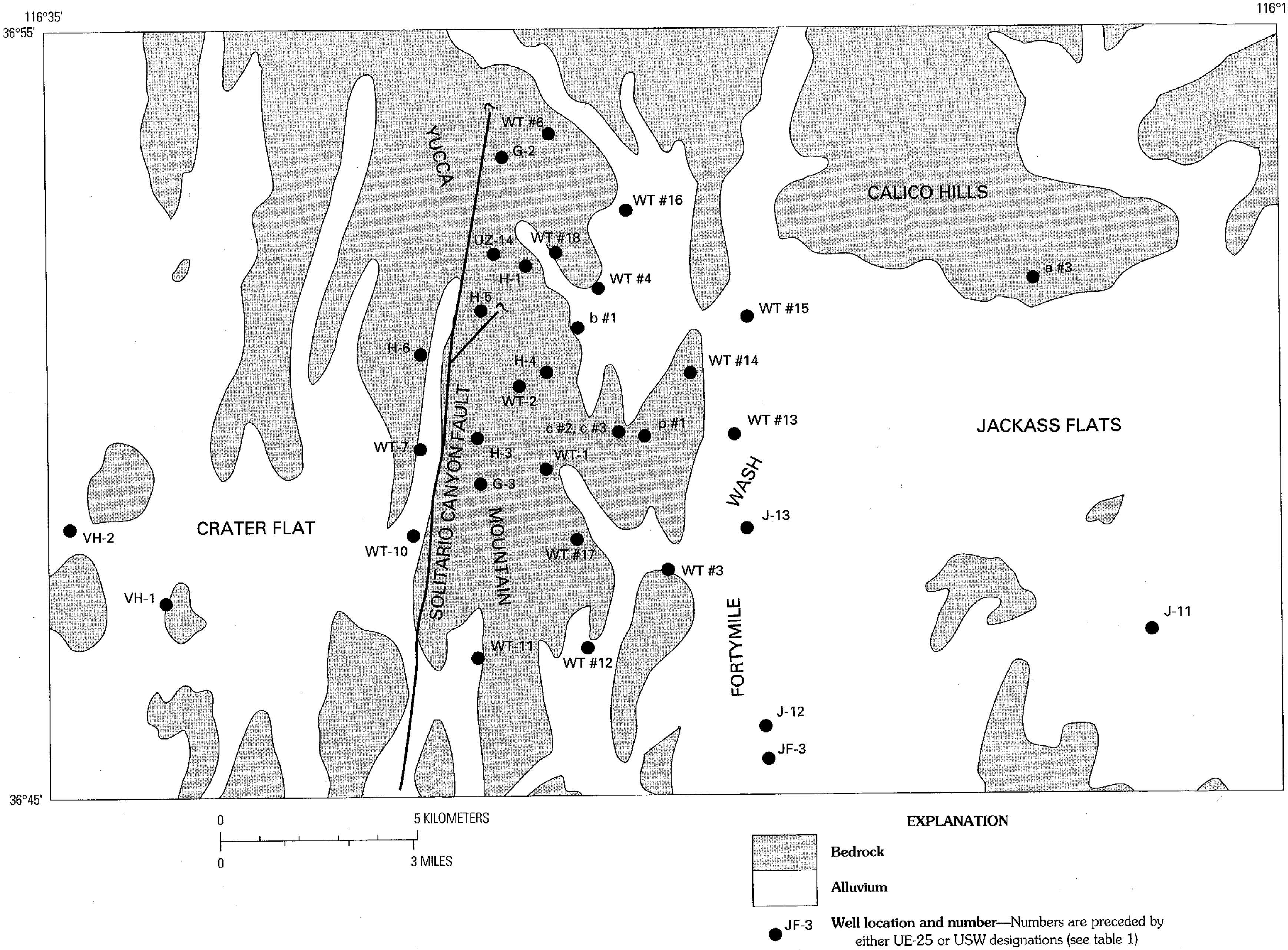

Figure 2. Location of wells in the vicinity of Yucca Mountain.

potentiometric surface of the uppermost saturated zone in the Tertiary volcanic rocks at Yucca Mountain. Potentiometric data for deeper parts of the volcanic-rock aquifer, as well as information related to the underlying Paleozoic carbonate aquifer, pertinent to the volcanic flow system, is also presented.

The potentiometric-surface map is primarily based on water levels obtained from a network of 28 wells that were monitored either hourly or monthly in 1993 (Tucci and others, *in press*). Water-level data for six other wells (USW VH-2, USW UZ-14, UE25a #3, UE-25c #2, UE-25c #3, and JF-3), for various time periods are also included to provide a more complete areal coverage of data. The locations of wells are shown in figure 2.

GEOLOGIC AND HYDROLOGIC SETTING

Yucca Mountain is located within a geologically complex region that lies in the Great Basin portion of the Basin and Range physiographic province. The geology in the south-central Great Basin consists of sedimentary rocks of Precambrian and Paleozoic ages, volcanic and minor sedimentary deposits of Miocene age, and surficial deposits comprising alluvial and playa sediments of Quaternary age. Mesozoic rocks are missing from the geologic sequence in this area, except possibly for a few small intrusions (Winograd and Thordarson, 1975, p. 9; Byers and others, 1976).

Yucca Mountain is composed of a thick sequence of extrusive volcanic rocks (Scott and Bonk, 1984; Sawyer and others, 1994). Gravity studies indicate that the volcanic rocks are 3,000 m in thickness beneath Yucca Mountain (Snyder and Carr, 1984). Well UE-25a #3 penetrates argillites and altered argillites of the Devonian and Mississippian age Eleana Formation (Sass and others, 1980, p. 6), which underlies the Calico Hills and possibly Jackass Flats. Well UE-25p #1 is the only borehole that penetrates Paleozoic carbonate rocks in the immediate vicinity of Yucca Mountain. This borehole is 1.5 km east of Yucca Mountain (fig. 2) and penetrated a Silurian age dolomite at a depth of 1,244 m (Craig and Robison, 1984). The Eleana Formation, which is stratigraphically above the dolomite, is missing at well UE-25p #1.

Detailed discussions of the geology of the Yucca Mountain area are given by many investigators, including Ross and Smith (1961), Lipman and others (1966), Byers and others (1976), Scott and Bonk (1984), Carr and others (1986), Diehl and Chornack (1990), Frizzell and Shulters (1990), and Sawyer and others (1994). Structurally, the Yucca Mountain area has many generally north-south trending faults (Scott and Bonk, 1984). The Solitario Canyon Fault (fig. 2) is of particular importance to the potentiometric levels in the area. The Solitario Canyon Fault is a north-south trending wrench fault, which to the south is downthrown on its western side and to the north is downthrown on the eastern side (Scott and Bonk, 1984). The hinge line of the fault, where the displacement changes, is perpendicular to the fault plane and is located approximately 1 km southeast of USW G-2. Offset on the fault may be as much as 250 m (M.P. Chornack, USGS, oral commun., 1992). Toward its southern extent, the Solitario Canyon Fault appears to widen and have more splays. Fault gouge and secondary-siliceous infillings are present along the fault plane (M.P. Chornack, USGS, oral commun., 1992). The geologic setting of the area was summarized by Ervin and others (1994), and that summary is not repeated here.

An upper volcanic flow system (fig. 3) is conceptualized as occurring above the Calico Hills Formation at water-level altitudes of about 1,100 m to more than 1,200 m. This system extends from Crater Flat, along the southern part of Yucca Mountain, to Jackass Flats. The lower volcanic flow system (fig. 3) occurs in fractured tuffs beneath the Calico Hills Group, primarily in the various members of the Crater Flat Group and constitutes the potentiometric surface of the uppermost saturated zone beneath much of Yucca Mountain and the western part of the small-gradient area. The lower system probably continues north of well USW H-1, but to the north, increasing lithostatic pressure tends to close the fractures and decrease the hydraulic conductivity.

The Eleana formation was described as a confining unit by Winograd and Thordarson (1975) and Waddell and others (1984). The uppermost potentiometric surface is within this unit in the Calico Hills, as represented by conditions at well UE-25a #3. The carbonate rocks penetrated by well UE-25p #1 comprise part of the lower carbonate aquifer of Winograd and Thordarson (1975). This aquifer is separated from the overlying volcanic flow systems by poorly permeable volcanic and clastic rocks of Tertiary age (R.R. Luckey, U.S. Geological Survey, written commun., 1994).

PREVIOUS WORK

Several potentiometric maps have been constructed on a sub-regional scale including maps of Waddell and others (1984), Czarnecki and Waddell (1984), and Robison (1984, p. 2). These maps show potentiometric contours near Yucca Mountain, including possible recharge and discharge areas, but do not focus specifically on Yucca Mountain. An additional map in the same report by Robison (1984, p. 4) shows the potentiometric surface around Yucca Mountain using primarily 1983 data.

VOLCANIC STRATIGRAPHY		HYDROSTRATIGRAPHY
Paintbrush Group	Tiva Canyon Tuff	Upper volcanic flow system
	Yucca Mountain Tuff	
	Pah Canyon Tuff	
	Topopah Spring Tuff	
Calico Hills Formation		Poorly-permeable volcanic rocks
Crater Flat Group	Prow Pass Tuff	Lower volcanic flow system
	Bullfrog Tuff	
	Tram Tuff	
Lithic Ridge Tuff		Poorly-permeable volcanic rocks

Figure 3. Generalized volcanic stratigraphy and associated hydrostratigraphy at Yucca Mountain.

Ervin and others (1994) described the potentiometric surface of the Yucca Mountain area based, primarily, on more accurate 1988 water-level data, and presented a map of the surface (Ervin and others, 1994, pl. 1). Prior to the present study, the 1988 map was the most recent potentiometric map available for the Yucca Mountain area. Ervin and others (1994) divided the map into three major regions: (1) A small-gradient area to the southeast of Yucca Mountain that comprises most of the study area; (2) a moderate-gradient area to the west of Yucca Mountain; and (3) a large-gradient area to the north. Ervin and others also discussed water-level trends, based on data from 1986–1989, and temperature-density adjustments to water levels.

WATER-LEVEL DATA

Description of Wells

Data on wells and average water levels used to construct the revised potentiometric-surface map are listed in table 1. The well designations beginning with either "USW WT" or "UE-25 WT" are holes that penetrate only the upper part (16 to 103 m) of the flow system in volcanic rocks. Well designations beginning with "USW H" are deeper hydrologic test holes that may monitor the water level in more than one interval, although the water levels reported in table 1 are from the uppermost sections of these wells.

Several boreholes were drilled as part of other studies or for special purposes, but are included in this study to provide a wide areal coverage: (1) UE-25c #2 and UE-25c #3 are part of a multiple-well complex designed for fracture-flow studies and for examining flow at borehole to borehole scale; (2) UE-25p #1 was drilled to penetrate to the Paleozoic carbonate rocks; (3) USW G-2 and USW G-3 are geologic boreholes that have been adapted to measure water levels; (4) J-12 and J-13 are water-supply wells; (5) JF-3 is an observation well for monitoring water levels to identify the effects of withdrawals from water-supply wells; and (6) wells USW VH-1 and USW VH-2 are boreholes that were drilled to investigate the volcanic rocks in Crater Flat. Most of these wells have been monitored for water levels on either a periodic or hourly basis since 1983 or 1984 (Robison and others, 1988).

Table 1. Summary of selected wells monitored for water levels at Yucca Mountain

[Water-level altitude is 1993 mean value unless otherwise indicated. Depths are in meters below land surface. Altitude is in meters above sea level]

Local-well number	Latitude	Longitude	Altitude of well casing (meters)	Water-level altitude (meters)	Drilled depth (meters)	Open interval depth (meters)	Geologic unit at water table
USW WT-1	36°49'16"	116°26'56"	1,201.11	730.28	515	471–515	Calico Hills[4]
USW WT-2	36°50'23"	116°27'18"	1,301.13	730.68	628	571–628	Prow Pass Tuff
UE-25 WT #3	36°47'57"	116°24'58"	1,030.11	729.72	348	301–348	Bullfrog Tuff
UE-25 WT #4	36°51'40"	116°26'03"	1,169.21	730.82	482	439–482	Calico Hills[4]
UE-25 WT #6	36°53'40"	116°26'46"	1,314.78	1,034.35	383	281–383	Do
USW WT-7	36°49'33"	116°28'57"	1,196.88	775.88	491	421–491	Topopah Spring[5]
USW WT-10	36°48'25"	116°29'05"	1,123.40	776.11	431	348–431	Do
USW WT-11	36°46'49"	116°28'02"	1,094.11	730.69	441	364–441	Do
UE-25 WT #12	36°46'56"	116°26'16"	1,074.74	729.42	399	345–399	Do
UE-25 WT #13	36°49'43"	116°23'51"	1,032.51	729.11	354	303–354	Do
UE-25 WT #14	36°50'32"	116°24'35"	1,076.05	729.66	399	346–399	Do
UE-25 WT #15	36°51'16"	116°23'38"	1,082.94	729.22	415	354–415	Do
UE-25 WT #16	36°52'39"	116°25'34"	1,210.63	738.27	521	473–521	Calico Hills[4]
UE-25 WT #17	36°48'22"	116°26'26"	1,124.06	729.69	443	394–443	Prow Pass Tuff
UE-25 WT #18	36°52'07"	116°26'42"	1,336.32	730.77	623	607–623	Calico Hills[4]
UE-25a #3	36°52'47"	116°18'53"	1,385.86	[6] 747.4	771	745–771	Eleana Formation
UE-25b #1	36°51'08"	116°26'23"	1,200.73	[1]730.61	1,220	471–1,199	Calico Hills[4]
UE-25c #2	36°49'45"	116°25'43"	1,132.18	[2]730.13	914	416–914	Do
UE-25c #3	36°49'47"	116°25'44"	1,132.41	[2]730.22	914	417–753	Do
UE-25p #1	36°49'38"	116°25'21"	1,114.21	[3]752.49	1,805	1,297–1,805	Do
USW G-2	36°49'05"	116°27'35"	1,553.86	1,020.28	1,831	242–806	Topopah Spring[5]
USW G-3	36°49'05"	116°28'01"	1,480.47	730.57	1,533	751–1,533	Tram Tuff
USW H-1	36°51'57"	116°27'12"	1,303.10	[1]730.92	1,829	573–673	Prow Pass Tuff
USW H-3	36°49'42"	116°28'00"	1,483.47	[1]731.21	1,219	752–1,114	Tram Tuff
USW H-4	36°50'32"	116°26'54"	1,248.74	[1]730.41	1,219	518–1,181	Prow Pass Tuff
USW H-5	36°51'22"	116°25'55"	1,478.94	[1]775.59	1,219	704–1,091	Bullfrog Tuff
USW H-6	36°50'49"	116°28'55"	1,302.06	[1]776.07	1,220	562–752	Prow Pass Tuff
USW VH-1	36°47'32"	116°33'07"	963.23	779.46	762	185–762	Tiva Canyon Tuff
USW VH-2	36°48'21"	116°34'37"	974.48	[7] 810.4	1,219	219–1,219	Alluvium
USW UZ-14	36°52'08"	116°27'40"	1,348.86	[8] 779	678	433–678	Prow Pass Tuff
J-11	36°47'06"	116°17'06"	1,049.45	732.21	405	328–396	Topopah Spring[5]
J-12	36°45'54"	116°23'24"	954.54	727.97	347	226–347	Do
J-13	36°48'28"	116°23'40"	1,011.47	728.47	1,063	283–1,063	Do
JF-3	36°45'28"	116°23'22"	945.04	727.95	396	224–347	Topopah Spring[5]

[1]Water-level altitude for uppermost interval of well. Other interval(s) also monitored.

[2]Water-level altitude based on 1989 data. Data not available for 1993.

[3]Water-level altitude for Paleozoic carbonates. Does not represent water level in the uppermost flow system.

[4]Calico Hills—abbreviation Calico Hills Formation.

[5]Topopah Spring—abbreviation Topopah Spring Tuff.

[6]Water-level altitude from Waddell and others (1984).

[7]Water-level altitude from Robison (1984).

[8]Estimated water-level altitude.

All wells listed in table 1, except UE-25p #1, are completed in the geologic unit that contains the potentiometric head of the uppermost saturated zone in the volcanic rocks of Tertiary age; UE-25p #1 is constructed to monitor the water level only in the underlying Paleozoic carbonate rocks. Water-level data from well UE-25p #1 were not used to construct the revised potentiometric map.

Water-level data for four wells that are not part of the routinely monitored water-level network at Yucca Mountain were also included in this study. Water levels in well JF-3 are monitored as part of another study, and the 1993 mean annual water-level altitude of this well is 727.95 m (R. La Camera, U.S. Geological Survey, written commun., 1994). The water-level altitude of 810.4 m for well USW VH-2 was reported by Robison (1984, table 1) as estimated from geophysical logs. The water-level altitude of 747.4 m for well UE-25a #3 was reported by Waddell and others (1984, fig. 8). The water-level altitude for well USW UZ-14 (779 m) is an estimate, based on the projected static water level once the well has equilibrated from drilling. The water level in this well has been slowly rising from an initial altitude of about 755 m in 1994 (R.R. Luckey, U.S. Geological Survey, written commun., 1994).

Although the wells are of different depths below the potentiometric surface of the uppermost saturated zone and are open to different geologic zones, water levels in most of the wells, particularly in the small-gradient area, represent a laterally continuous aquifer system. The water levels of the wells in the small-gradient area form an apparently logical distribution of potentiometric heads. This phenomena may result from the presence of many faults and fractures—creating a well-connected aquifer.

Accuracy and Precision

The accuracy of the periodically measured water-level data for 1988–90 is approximately 0.11 m with a precision of about 0.01 m (Boucher, 1994). The accuracy and precision of measurements obtained since 1990 are believed to be about the same as the 1988–90 measurements, because the same procedures were followed and the same or similar equipment were used to obtain the data. A history of measurement techniques used at Yucca Mountain is discussed by Robison and others (1988).

POTENTIOMETRIC SURFACE

The saturated zone at Yucca Mountain consists of volcanic aquifers in tuffs and a deeper Paleozoic carbonate aquifer of an unknown areal extent. The uppermost aquifer in the volcanic rocks may be unconfined or confined depending upon the areal location of the point being measured.

Flow in the volcanic rocks at Yucca Mountain occurs primarily in fractures while flow in the matrix of the rock is secondary (Nelson and others, 1991, p. 38). This phenomena may explain why the potentiometric surface in the uppermost saturated zone occurs in rocks of differing ages (table 1), and why ground-water flow occurs in differing formations.

Description and Explanation of the Potentiometric Surface

The revised potentiometric-surface map for 1993 is shown on figure 4. The water levels were contoured using contour intervals of 20 m (from 740 to 800 m) and 0.5 m (from 728 to 732 m). Placement of contours was determined by a combination of interpolation between points and use of hydrogeologic knowledge. An implicit assumption in the interpolation is that there is a uniform variation in the water level between wells. There are not enough data points to discern large changes in water levels across features such as faults, except possibly the Solitario Canyon Fault (fig. 2).

Water-level altitudes range from about 728 m, southeast of Yucca Mountain, to more than 1,034 m north of Yucca Mountain (fig. 4). Water-level altitudes in Crater Flat, west of Yucca Mountain, range from about 775 m to 810 m (fig. 4). Mean annual potentiometric levels for the lower volcanic flow system range from about 730 m to about 786 m (table 2).

Potentiometric levels are contoured from 740 to 800 m, north and west of Yucca Mountain, using a 20-m contour interval because of the moderate to large hydraulic gradients in these areas. Potentiometric levels are contoured from 728 to 732 m, east of Yucca Mountain, using a 0.5-m contour interval because of the small hydraulic gradient in this area. Potentiometric levels for deep intervals below the water table are not contoured because of the relatively few available data points.

If the aquifer is assumed to be isotropic and areally continuous, directions of ground-water flow can be inferred from the potentiometric-surface map. Assuming these conditions, ground water flows from the north and west toward Yucca Mountain, continuing east to an area just east of Fortymile Wash, where flow

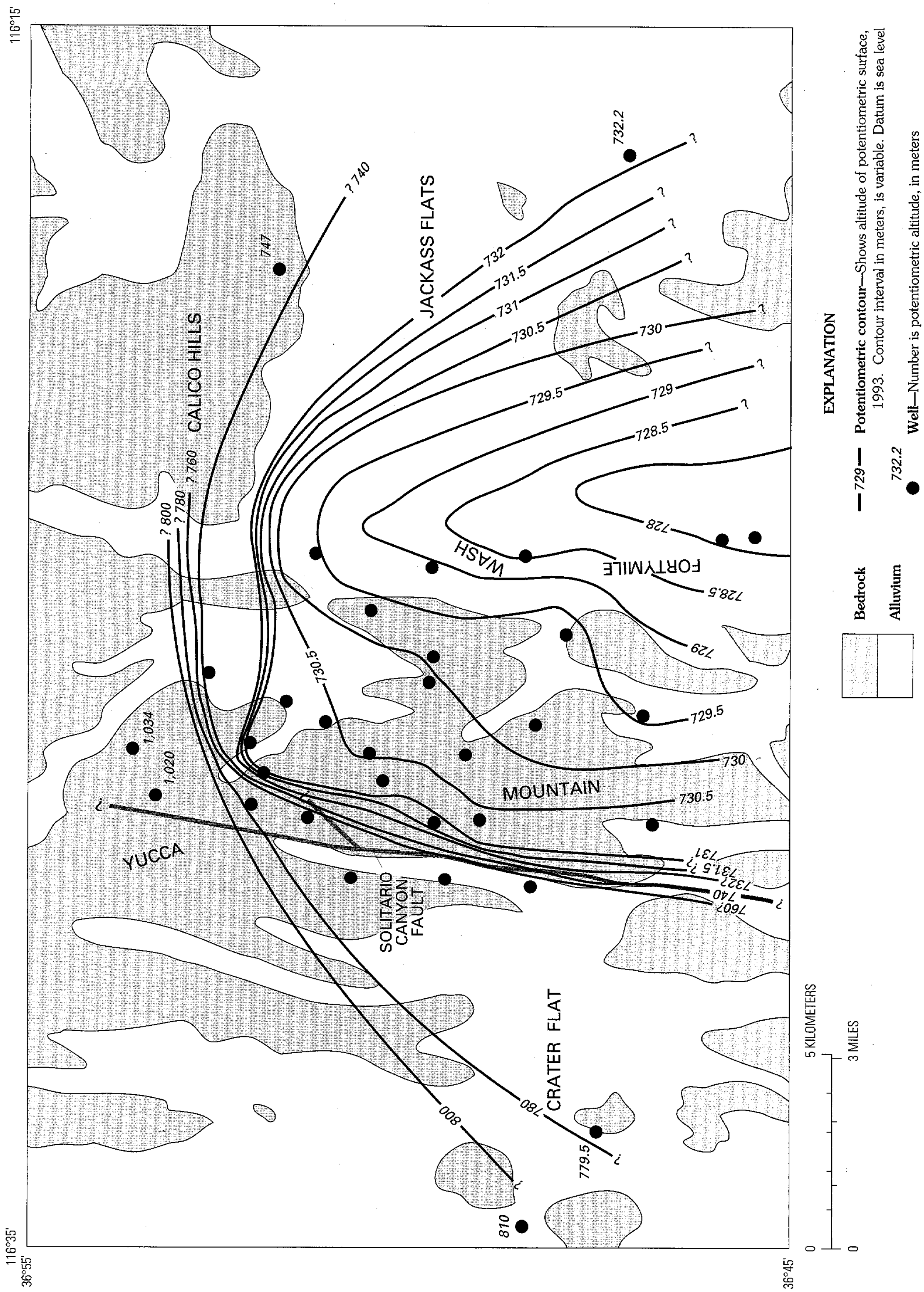

Figure 4. Potentiometric surface of Yucca Mountain and vicinity, 1993.

is to the south. Ground water would also flow from the eastern part of Jackass Flats to an area just east of Fortymile Wash, and south toward the Amargosa Desert. Because the nature of the hydraulic characteristics of the volcanic-rock aquifer could be isotropic or anisotropic and because the influence of faults on the direction of ground-water flow are not known at present, alternative concepts of ground-water flow may also be considered equally valid.

Table 2. Mean annual 1993 potentiometric levels for wells monitoring the lower volcanic and carbonate flow systems at Yucca Mountain

Well	Depth interval (meters)	1993 Mean altitude (meters above sea level)
USW H-1, Tube 1	1,783–1,814	785.58
USW H-1, Tube 2	1,097–1,123	735.58
USW H-1, Tube 3	716–765	730.64
USW H-3, lower interval	1,061–1,219	756.83
USW H-4, lower interval	1,118–1,219	730.41
USW H-5, lower interval	846–1,219	775.72
USW H-6, lower interval	752–1,220	775.97
UE-25b #1, lower interval	1,199–1,220	729.92 [1]
UE-25c #3, lower interval	753–914	730.49 [2]
UE-25p #1	1,297–1,805	752.39 [3]

[1]Only one measurement available for 1993.

[2]No data available for 1993. Value is 1990 mean altitude.

[3]Monitors Paleozoic carbonate rocks.

Based on the shape of the potentiometric contours, the area just east of Fortymile Wash appears to act as a drain for the ground-water flow system; however, recharge is believed to occur in the upper reaches of the wash. The shape of the contours in this area is controlled by the relatively high potentiometric level (732.21 m) in well J-11. Additional data are needed between J-11 and Fortymile Wash to further define the shape of the contours in this area.

The map can be divided into three major regions (fig. 5): (1) A small-gradient area—to the east and southeast of Yucca Mountain where water levels range from about 728 to 732 m and most wells are located; (2) a moderate-gradient area—to the west of the mapped extent where water levels range from about 740 to 800 m (defined by wells USW WT-7, USW WT-10, USW H-5, USW H-6, and USW VH-1); and (3) a large-gradient area—to the north of the mapped area where water levels range from about 738 to 1,034 m (defined by wells UE-25 WT #6, UE-25 WT #16, and USW G-2). The current map primarily focuses on the small-gradient area because, of the three regions, it is the area best defined by the data and is downgradient of the potential repository location.

The three regions shown on figure 5 are based largely upon variations in potentiometric head and gradient. The small-gradient area ranges in hydraulic gradient from about 0.0001 to 0.0004. The moderate-gradient area ranges in hydraulic gradient from 0.02 to 0.04—two orders of magnitude greater than the small-gradient area. The large-gradient area has a hydraulic gradient of about 0.11—about three orders of magnitude greater than the small-gradient area and one order of magnitude greater than the moderate-gradient area.

The area of small gradient (fig. 5), where the potentiometric surface is nearly horizontal, could result from either flow through highly transmissive rocks or low ground-water flux. It is difficult to ascertain the degree to which each mechanism or combination of the two is affecting water levels in the small-gradient area.

Potentiometric contours are relatively widely spaced immediately east of Yucca Mountain, particularly between wells UE-25 WT #17 and UE-25 WT #3 (fig. 4). The reason for this very small gradient (0.00013) is not known, although it is consistent with data for 1988 (Ervin and others, 1994, pl. 1). Hydraulic gradients are slightly less west of Fortymile Wash than east of the wash.

The potentiometric surface in the moderate-gradient area (fig. 5) appears to be controlled by the Solitario Canyon Fault and a splay of that fault near well USW H-5 (Ervin and others, 1994, p. 9). Potentiometric contours are closely spaced and parallel to the Solitario Canyon Fault on the west side of Yucca Mountain (fig. 4), and the fault appears to be a barrier to ground-water flow from the west. Ervin and others (1994, p. 9) attributed the influence of the fault to low permeability fault gouge within the fault zone or to offset of rock units of differing permeabilities. Although the Solitario Canyon Fault may impede west-to-east ground-water flow particularly south of the hinge line of the fault, flow may occur south along the fault.

Several alternate conceptual models for the large-gradient area (fig. 5) have been proposed (Fridrich and others, 1991; Czarnecki and Wilson, 1991; Szymanski, U.S. Department of Energy, written commun., 1989; Fridrich and others, 1994); however, the concept presented by Ervin and others (1994, pp. 9–11) is also presented here. The following discussion is taken directly from their report.

The large-gradient area of the potentiometric-surface map is based on a conceptual model that the large-hydraulic gradient represents a semi-perched system—consisting of an unconfined water body with a

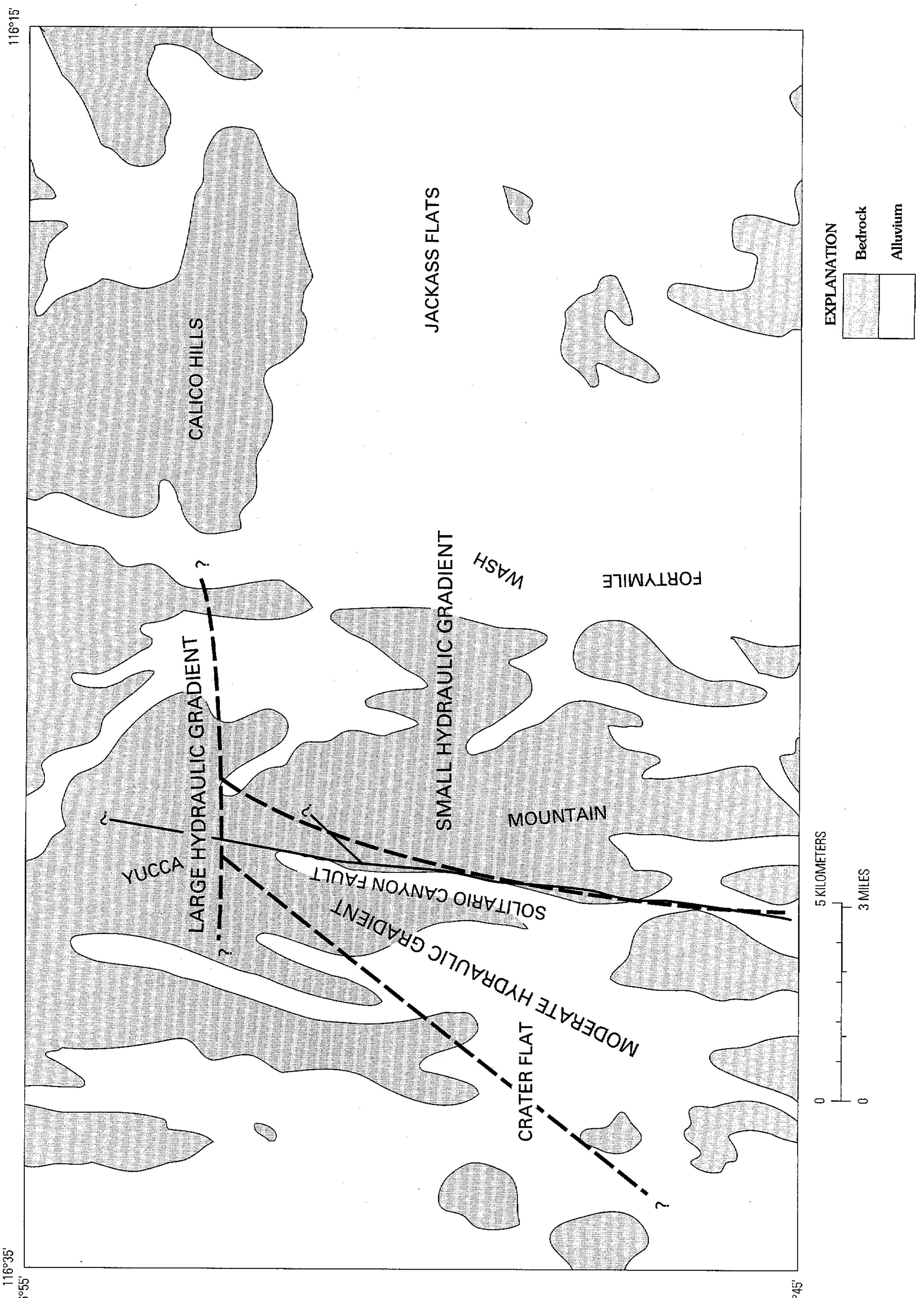

Figure 5. Large-, moderate-, and small-gradient areas at Yucca Mountain.

higher water level set above a confined water body with a lower water level with an intervening zone of low permeability that is fully saturated (Meinzer, 1923, p. 41). In such a system, flow in the upper and lower more-permeable zones would be predominantly horizontal while flow in the low-permeability zone would be predominantly vertical. Winograd and Thordarson (1975, p. 50) note that semi-perched water is not uncommon at and in the vicinity of the Nevada Test Site.

At the north end of Yucca Mountain, the upper flow system is limited. Water in the upper flow system may move primarily vertically through the poorly permeable Calico Hills Tuff and ultimately reach the lower volcanic flow system. Hydraulic gradient in the lower system probably increases to the north as hydraulic conductivity decreases.

Comparison to Previous Maps

The 1993 potentiometric map (fig. 4) represents a larger area than those presented by Robison (1984) and Ervin and others (1994) in order to better conceptualize potential hydrologic boundaries for ground-water flow modeling of the Yucca Mountain area (U.S. Department of Energy, 1988). The contour intervals used in the present map were also somewhat different from those of previously published maps. The 0.5-m contour interval used in the small-gradient area is less detailed than the 0.25-m interval of Ervin and others (1994, pl. 1); however, the data would support such an interval if presented at a different scale.

Ervin and others (1994) described differences between their map and previous maps, and those differences and the reasons for them are applicable for the present map as well. Both the 1988 and 1993 maps are based on data that has had the following corrections applied: (1) More accurate altitude measurements of the top of the borehole casing; (2) corrections for equipment wear, and; (3) corrections for mechanical stretch and thermal expansion of the steel tapes used for measuring. Large scale features, including the three major areas previously discussed, have essentially remained the same on all maps. However, by extending the area of the 1993 potentiometric-surface map, the contours in the small-gradient area form a "V" pointing to the north, just to the east of Fortymile Wash. This feature was not evident on previous maps.

Another difference between the 1993 potentiometric-surface map and previously published maps is the manner in which the moderate- and large-hydraulic gradient areas are shown. The moderate- and large-gradient areas are represented by Ervin and others (1994, pl. 1) by shaded patterns rather than contours. Contours in Ervin and others (1994) terminate in the general vicinity of Solitario Canyon and USW H-5 and north of USW H-1 and the small-gradient area.

Mean annual potentiometric levels for 1993 are not significantly different from the 1988 mean levels. Water levels in half of the wells were lower, and half were higher, in 1993 than in 1988; water levels in well USW VH-1 were the same in 1993 as in 1988 (table 3). The largest differences were for wells UE-25 WT #6 (-0.75 m) and USW H-3 (-0.51 m). The mean absolute differences in water level for all wells was 0.13 m. The difference in water levels for UE-25 WT #6 may be related to a lowering of water levels in that well following earthquakes in the region in 1992 (O'Brien and others, 1995). The difference in water level for USW H-3 is related to the lower water levels observed following resetting of the packer in 1991, that separates the upper and lower intervals monitored in the well.

Table 3. Difference between 1993 and 1988 mean annual water levels at Yucca Mountain

Well	Difference in water level (meters)
USW WT-1	- 0.12
USW WT-2	- 0.03
UE-25 WT #3	+ 0.15
UE-25 WT #4	+ 0.12
UE-25 WT #6	- 0.75
USW WT-7	+ 0.18
USW WT-10	+ 0.19
USW WT-11	- 0.03
UE-25 WT #12	- 0.10
UE-25 WT #13	+ 0.13
UE-25 WT #14	- 0.05
UE-25 WT #15	- 0.02
UE-25 WT #16	- 0.05
UE-25 WT #17	+ 0.05
UE-25 WT #18	- 0.03
USW G-3	+ 0.01
USW H-1	- 0.03
USW H-3	- 0.51
USW H-4	+ 0.08
USW H-5	+ 0.12
USW H-6	+ 0.12
USW VH-1	0.00
J-13	+ 0.02

NOTE: Differences (1993–1988) are for uppermost interval monitored interval in each well.

WATER-LEVEL TRENDS

Selected water-level data from wells used for the 1993 potentiometric-surface map (table 1) were examined for yearly water-level trends. These trends were examined to determine if water-level responses are similar among wells over time, and to determine the effect of using water-level data of different years (where 1993 data were not available) to construct the revised potentiometric-surface map (fig. 4). Yearly trends are defined as those that occur over the span of years and indicate either a rise, fall, or no change in the water level with respect to time. Short-term and cyclic trends are noted in the water levels at Yucca Mountain and comprise the effects of barometric changes, earth tides and possibly other phenomena, but were not analyzed for this report. For yearly trends, the accuracy of the water-level measurement is not as critical as the precision between measurements (Robison and others, 1988, p. 19). In addition, for yearly water-level trend analysis, the period of record must be of sufficient length to prevent short-term and/or cyclic variations from adversely affecting the analysis.

Water-level data were examined for trends from 1986–93. Earlier data were not used because they were collected before measurement consistency in the water-level network had been established. As the network evolved, measurement techniques changed resulting in significantly different means and standard deviations for data measured between the various techniques. Data from earlier measurement techniques are less reliable than those developed later and were not considered in the analysis. Trends discussed in this section update those discussed by Ervin and others (1994), which were considered preliminary due to the short period of record (1986–89) over which they were analyzed. Although this analysis covers an eight-year period, it is a relatively short period and the results should be viewed accordingly.

Yearly mean water levels were calculated for each well in the analysis. For periodically measured wells (USW WT-1, UE-25 WT #4, USW WT-7, USW WT-10, UE-25 WT #12, UE-25 WT #14, UE-25 WT #15, UE-25 WT #17, and J-13), the number of measurements per year was usually 12, and these were used to calculate the yearly means. For continuously monitored wells (USW WT-2, UE-25 WT #3, UE-25 WT #6, USW WT-11, UE-25 WT #13, UE-25 WT #16, UE-25 b #1, UE-25p #1, USW G-3, USW H-1, USW H-4, USW H-5, and USW H-6), daily values obtained from the U.S. Geological Survey National Water Information System (NWIS) database were used to calculate the yearly mean. The summation of the monthly and daily values removed the barometric-pressure and tidal effects in the water-level data. This removed the autocorrelation effects noted by Ervin and others (1994).

Trends were analyzed by a linear least-squares regression of time verses water level. Table 4 summarizes results from this analysis for the wells examined, and reports the slope and standard deviation of the least-squares fit curve and whether or not the water levels exhibited a statistically significant trend.

Table 4. Results of trend analysis of water levels at Yucca Mountain, 1986–93

Well	Slope (meters/ year)	Standard deviation (meters/ year)	Significant trend
USW WT-1	-0.001	0.009	None
USW WT-2	0.017	0.01	None
UE-25 WT #3	0.04	0.01	Positive
UE-25 WT #4	0.02	0.008	None
UE-25 WT #6	0.07	0.08	None
USW WT-7	0.02	0.007	Positive
USW WT-10	0.02	0.004	Positive
USW WT-11	0.005	0.008	None
UE-25 WT #12	-0.002	0.006	None
UE-25 WT #13	0.01	0.01	None
UE-25 WT #14	0.0001	0.0005	None
UE-25 WT #15	0.0006	0.002	None
UE-25 WT #16	0.029	0.01	None
UE-25 WT #17	0.005	0.007	None
UE-25b #1	0.02	0.008	None
UE-25p #1	0.008	0.02	None
USW G-3	-0.003	0.01	None
USW H-1	0.04	0.01	None
USW H-4	0.01	0.006	None
USW H-5	0.02	0.01	None
USW H-6	-0.003	0.02	None
J-13	0.02	0.02	None

Significance of the slope of the curve was tested using the t distribution (Neter and others, 1990, p. 69) with the null hypothesis being that the slope of the curve equalled zero. A trend was considered to be statistically significant if the null hypothesis was rejected at a 95-percent confidence level.

Residuals of the regression for each well were examined for their normality and their autocorrelation (two assumptions of linear regression). Residuals appeared less autocorrelated and more normal than those determined by Ervin and others (1994) with the effects of barometric pressure and tidal effects averaged out.

Water-level data from three of the wells (UE-25 WT #3, USW WT-7, USW WT-10) exhibit apparent positive trends that are statistically significant (table 4). Several values listed in table 4 are less than the precision of the water-level measurements (0.01 m); however, these are calculated values and are presented to allow for evaluation of the trend analysis.

The trend in well UE-25 WT #3 is influenced by the first three years of problematic continuous monitoring (Luckey and others, 1993, p. 39–40). These data may be less reliable than those obtained from periodic manual measurements, due to problems with the transducers used to obtain the continuous data. Water levels in wells USW WT-7 and USW WT-10 exhibit slight, positive water-level trends. Both of these wells are located just west of the Solitario Canyon Fault (fig. 2); however, water levels in well USW H-6, which is also located west of the fault, do not show a statistically significant trend.

Water-level trends were judged by the authors to be small enough not to be a factor in using the averaged 1993 water-level data in constructing the revised potentiometric-surface map. Analysis of trends from year to year shows a decrease in the rate of change in the water levels with time. Results of the trend analysis, showing little or no trend over the time period measured, support the use of water-level data from years other than 1993 to construct the potentiometric-surface map, where 1993 data are not available.

SUMMARY

Average water levels, mostly collected during 1993, are compiled in a revised potentiometric-surface map of the Yucca Mountain area to update previous maps. Prior to construction of the 1993 potentiometric-surface map, the most recent map was for 1988 water-level data.

Water levels are contoured with a 20-m contour interval, with additional 0.5-m contours in the small-gradient area southeast of Yucca Mountain. Water levels range from about 728 to about 1,034 m above sea level. Potentiometric levels in the lower volcanic flow system range from about 730 to 786 m above sea level. Mean annual 1993 water levels differ from mean annual 1988 levels by an average of 0.13 m. Mean annual 1993 water levels from half of the wells were higher, and water levels in the other half were lower than 1988 levels.

The revised potentiometric-surface map can be divided into three regions consisting of a small-hydraulic gradient area, a moderate-hydraulic gradient area, and a large-hydraulic gradient area. Gradients in these areas are 0.0001 to 0.0004, 0.02 to 0.04, and about 0.11, respectively. The general ground-water flow direction downgradient of Yucca Mountain is east-southeast, if flow is assumed to be perpendicular to the potentiometric-surface contours. This assumption may not hold true because of heterogeneity and anisotropy, and because of the influence of fractures and faults on ground-water flow. An explanation of the potentiometric surface at Yucca Mountain is posed; whereby the nearly flat surface of the small-gradient area results from flow through highly transmissive rocks or low ground-water flux through the system; the higher water levels of the moderate-gradient area are from impedance of flow across the Solitario Canyon Fault and a splay of the fault; and the much higher water levels of the large-gradient area may be due to a semi-perched ground-water system north of Yucca Mountain.

Data for selected wells, used to create the revised map, were examined for yearly trends from 1986–93. Seasonal and other cyclic trends were not examined in this analysis. Three of the wells exhibited statistically significant trends from a least-squares regression of the data. The trend in well UE-25 WT #3 may be influenced by monitoring equipment problems during the first three years of monitoring. Trends in wells USW WT-7 and USW WT-10 are similar. Both of those wells are located just to the west of the Solitario Canyon Fault, west of Yucca Mountain; however, well USW H-6, which is also located just to the west of the fault, did not exhibit any significant water-level trend.

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